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DEVELOPMENT OF AN ELECTROPHORETIC IMAGE DISPLAY

QUARTERLY TECHNICAL REPORT

November 1, 1979 to January 31, 1980

Sponsored by

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Principal Investigator: Richard Liebert (914) 762-0300

Monitored by: Dr. Robert E. Kahn

Contract Period: 20 Sept. 1979 - 30 Sept. 1981

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The size of the ion-beam milled control-grid structure was increased to 2.0 in. x 2.6 in. (from 0.75 in. x 0.75 in.); the diameter of the uniform area is 2.7 in. Fabrication techniques for this larger size are being developed. The design of a working display is nearly complete. Using the results of the computer model, the dimensions of the display were chosen. The potential wells will be 30 μm x 102 μm with 6 μm wide walls. The maximum separation between electrodes will be 62 μm, and the wells will be 12 μm deep. The display will have 16 rows of 32 characters in a 5 x 7 dot matrix font with a resolution of 2 lp/mm. The active area will be 2.22 in. x 1.43. in and contain 32,224 pixels. It was decided to use In_2O_3 as the material for the grid electrode instead of aluminum; deposition of the In_2O_3 will begin as soon as the sputtering system is modified.

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PREFACE

This work is being performed by Philips Laboratories, a Division of North American Philips Corporation, Briarcliff Manor, New York under the overall supervision of Dr. Barry Singer, Director, Component and Device Research Group. Mr. Richard Liebert, Metallurgist, is the Program Leader; Ms. Beverly Fitzhenry, Chemist, is responsible for evaluation and testing of electrophoretic suspensions; Mr. Joseph Lalak, Electronic Engineer, is responsible for cell fabrication and technology.

This program is sponsored by the Defense Advanced Research Agency (DARPA) and was initiated under Contract No. MDA903-79-C-0439. Dr. Robert E. Kahn is the Contracting Officer's Technical Representative for DARPA.

The work described in this second Quarterly Technical Report covers the period from 1 November 1979 to 31 January 1980.

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SUMMARY

The size of the ion-beam milled control-grid structure was increased to 2.0 in. x 2.6 in. (from 0.75 in. x 0.75 in.); the diameter of the uniform area is 2.7 in. Fabrication techniques for this larger size are being developed. The design of a working display is nearly complete. Using the results of the computer model, the dimensions of the display were chosen. The potential wells will be 30 μm x 102 μm with 6 μm wide walls. The maximum separation between electrodes will be 62 μm, and the wells will be 12 μm deep. The display will have 16 rows of 32 characters in a 5 x 7 dot matrix font with a resolution of 2 lp/mm. The active area will be 2.22 in. x 1.43 in. and contain 32,224 pixels. It was decided to use In_2O_3 as the material for the grid electrode instead of aluminum; deposition of the In_2O_3 will begin as soon as the sputtering system is modified.

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1. INTRODUCTION

The effort during this quarter was directed toward fabrication of devices as large as 2 in. x 3 in. The ion-beam milling and Mylar sealing technologies described in the previous Quarterly Technical Report were further developed. The computer-aided design work was completed. The design of the deliverable device for Phase I of this contract was finished, and drawings for the necessary photolithographic masks have been started. A decision to replace the reflective-aluminum grid electrode with transparent tin-doped indium oxide electrode has been made.

2. LARGE-AREA ION-BEAM MILLING

2.1 Technological Aspects

Since void-free seals could be more reliably obtained without excessive deformation of the Mylar when an epoxy adhesion layer is used, we have adopted this technique for fabricating large-area devices.

Mylar sheet 12 μm thick was coated on one side with epoxy and cut into 2-1/2 in. x 3-1/4 in. pieces. However, when these pieces were sealed to In_2O_3 coated glass substrates, the seals were not void-free. This was partially due to the presence of particulate contamination. Cleaning, handling, and sealing procedures were modified to largely eliminate this problem; however, void-free seals have still not been obtained. This was traced to deflection of the pressing platen and non-flatness of the glass substrates, resulting in non-uniform pressure over the seal area. A stiffer platen is being made, and flatter substrates are being considered as is the use of a compliant member, such as silicone rubber, between the platen and Mylar.

Although void-free samples have not yet been made, recent ones were suitable for further processing. These were coated with

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aluminum and a photoresist pattern applied. Because of their large size, the photoresist exposure system previously employed could not be used. Instead, a vacuum print frame and a 5 in. aperture exposure system were used. Additional experience and adjustment of this system is needed to obtain the desired line-width control and uniformity. We have considered wet chemical etching of the aluminum to obtain better line definition than is now possible with ion-beam milling since the former is more tolerant of variations in photoresist thickness at the edge of the line. Wet etching could be used if we are unable to obtain suitable resist patterns with the present exposure system. Improved post-baking of the photoresist has resulted in patterns which withstand ion milling; both methods are being evaluated.

2.2 Fabrication of Large-Area Devices

Using the ion-beam milling conditions and rates determined during the last quarter, 2-1/8 in. x 2-3/4 in. areas were milled. The nominal diameter of the beam is 3 in., and we wanted to determine the maximum usable diameter under the constraints that essentially all the Mylar should be removed from the potential wells and that nowhere should all of the underlying In_2O_3 be removed. The usable diameter was found to be 2.7 in. This dimension determines the maximum diagonal of the active area of a deliverable device for Phase I of this program.

Several large-area cells were assembled for testing. The electrical opens previously reported have been eliminated. However, electrical shorts have prevented the operation of these devices in the triode mode. In some cases, the location of the shorts could be determined; these occurred under the perimeter seal. This seal, made with 50 μm thick Mylar coated on both sides with epoxy, is between the aluminum coating on the 12 μm Mylar and the In_2O_3 on the opposite substrate. Since shorts between the aluminum and the In_2O_3 under the 12 μm Mylar

occurred only after the perimeter seal was made, that operation is assumed to be the cause. Glass chips from the edges of the substrates seem to be penetrating the 12 μm Mylar, thereby bringing the aluminum into contact with the In_2O_3. Several steps are being taken to eliminate these shorts. It is encouraging that no shorts have been detected in the milled portion of the grid structure.

The use of an evaporated layer of SiO_x (where x is between 1 and 2) between the In_2O_3 and epoxy-coated Mylar is being investigated. Since SiO_x is a hard material with good dielectric properties, it could aid in preventing shorts between the aluminum and In_2O_3. Also, it would act as a sacrificial layer during ion-beam milling of the Mylar to prevent destruction of the In_2O_3 during the over-milling used to ensure complete removal of the Mylar. In this regard, the milling rate of SiO_x under Mylar milling conditions is only 75 Å/min. This gives a 30:1 differential when compared to 2000 Å/min for Mylar. Additionally, SiO_x could improve the optical properties of the device by using it as an antireflection coating for the In_2O_3. Investigation of SiO_x will continue during the next quarter.

Several shorted devices were filled with electrophoretic suspension and tested as diodes (i.e., grid electrode and the electrode at the bottom of the wells at the same potential). These devices were used to judge the uniformity of the ion-beam milling process and to judge the contrast and brightness of the display. The loss of contrast due to the high reflectivity of the aluminum grid electrode was observed, especially in specular reflection. The effects of diffraction from the metal grid were also noticeable.

It has been decided to attempt replacement of the reflective aluminum with transparent In_2O_3 as the grid electrode. A literature search has indicated the feasibility of depositing In_2O_3 with acceptable optical and electrical properties onto plastic films such as Mylar. A planar rf sputtering system will be modified for this purpose.

3. MATERIALS INTERACTIONS

During the last quarter, an operating life test was begun to assess the epoxy-coated Mylar seal. At that time over 10^3 hr had elapsed without a failure. Now, after 3.1×10^3 hr and 4.5×10^7 switches, failures have occured. Failures are defined as local nonuniformities in the pigment distribution which result in objectionable contrast differences under normal viewing conditions. One of twelve epoxy-sealed cells failed; however, this may have been due to improper sealing of the fill-hole, resulting in a leak. One of the five control cells without epoxy also failed, and one is failing. Four of the epoxy-sealed cells are failing, but two of them were purposely heated for less than the desired time during sealing. Thus, only two of ten cells sealed with epoxy-coated Mylar by the accepted procedure are failing. We conclude that the failure rate for the test group is no higher than that for the control group. Furthermore, there has been no visible attack of the seals in either group by the suspension. Therefore, the use of epoxy-coated Mylar should not shorten the life of displays fabricated with this material.

A test has begun to determine if the dyes used in our electrophoretic suspension have adverse effects on Mylar. After five weeks of storage in dyed solvent, Mylar sheets were inspected for color change. The BASF OSDB-BB black dye did show some slight surface adsorption, but this could be removed with vigorous rubbing. Neither of the Automate dyes, Red 11 or Blue 10, had any noticeable effect on the Mylar. Since none of the dyes were absorbed by the Mylar, their use in Mylar control-grid displays seems warranted at this time. This test will continue.

Another test will begin during the next quarter. Cells with Mylar-covered electrodes will be filled with dyed solvent and subjected to electrical stress. These cells are designed to test both plain and ion-beam milled Mylar under both positive and negative bias.

4. DEVICE DESIGN

4.1 Computer Modeling

The two-dimensional model of the control-grid EPID has been implemented on the computer and coupled with available library routines for x-y plotting, contour plotting, and pseudo three-dimensional plotting. Calculations were done with the following dimensions kept constant. The depth of the wells was always made 12 μm since: Mylar is readily available in this size, good brightness can be obtained with 12 μm thick pigment layers, and unnecessarily high addressing voltages are not required. The thickness of the perimeter seal was fixed at 50 μm since: good contrast can be obtained, anode potentials are reasonable, and the Mylar is available. These choices result in two possibilities for the overall cell thickness, 50 μm or 62 μm, because the perimeter seal may be directly between the In). electrodes on the substrates or may be between the control grid electrode and the In_2O_3 electrode on the opposite substrate. The model was used to investigate both cases, but only results for the 62 μm case are reported here.

It is desirable to maximize the open area in the grid electrode to achieve high brightness and contrast. However, since large center-to-center spacing and narrow walls require larger addressing potentials than desired to control the motion of the pigment, it was decided to investigate grid geometries with about 80% open area.

The resolution of the display influences the choice of grid dimensions. At 2 lp/mm, each pixel and isolation line together should occupy 250 μm. Wall dimensions much less than 5 μm would strain our photolithographic capability; widths greater than 6 μm rapidly reduce the open area. Making the wells rectangular rather than square increases the open area, and since the two-dimensional model only considers the separation of the grid lines in one direction, this is a conservative

approach. We have therefore considered center-to-center spacings which are factors of approximately 250 μm, wall widths of 5 μm and 6 μm, and well lengths of two or three times the center spacing. Table 1 shows the percent open area for some possible choices.

TABLE 1: Percent Open Area.

Spacing μm	Factor	Pixel Size μm	2X Spacing		3X Spacing	
			5 μm Wall	6 μm Wall	5 μm Wall	6 μm Wall
25	10	250	72%	67%	75%	70%
28	9	252	75%	70%	77%	73%
31	8	248	77%	73%	79%	75%
36	7	252	80%	76%	82%	79%
42	6	252	82%	80%	85%	82%

Four combinations yielding 79% and 80% were selected for further study. In all four cases the potential of the grid electrode (V_R) was set for zero, and the potential of the collection electrode (V_A) was made 30 V. This represents the "Hold" condition, a critical phase of device operation, in which pigment is to be retained in the potential well. A series of calculations was made with the potential at the bottom of the wells (V_C) adjusted from 6 V to 18 V in 2 V increments. The potential along the center line of the well was plotted for each of the four geometries and seven different well potentials. A typical plot is shown in Figure 1. Data from 28 such plots was used to construct Figures 2 and 3. Figure 2 shows the position of the potential minimum as a function of V_C with the dimensions of the well as a parameter. Figure 3 shows the depth (in volts) of the potential minimum.

From Figure 2 one can see the effect that reducing the spacing and increasing the width of the wall has on lowering the potential V_C necessary to bring the potential minimum to the top of the well. Figure 3 indicates that narrower spacing and wider walls increase the potential difference between the electrode at

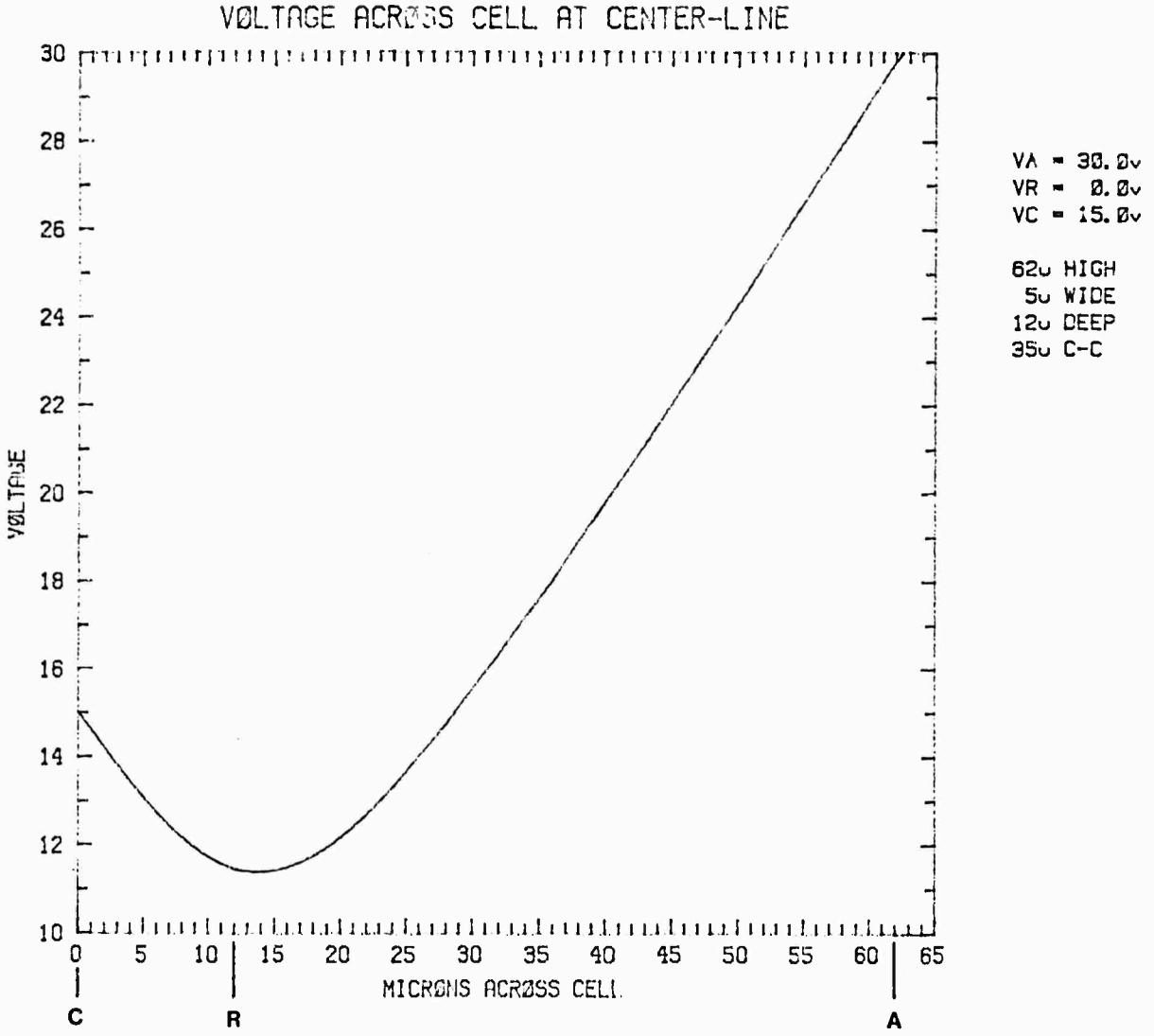

VØLTAGE ACRØSS CELL AT CENTER-LINE
VØLTAGE
30
28
26
24
22
20
18
16
14
12
10
0
5
10
15
20
25
30
35
40
45
50
55
60
65
MICRØNS ACRØSS CELL
C
R
A
VA = 30.0v
VR = 0.0v
VC = 15.0v
62u HIGH
5u WIDE
12u DEEP
35u C-C

Figure 1

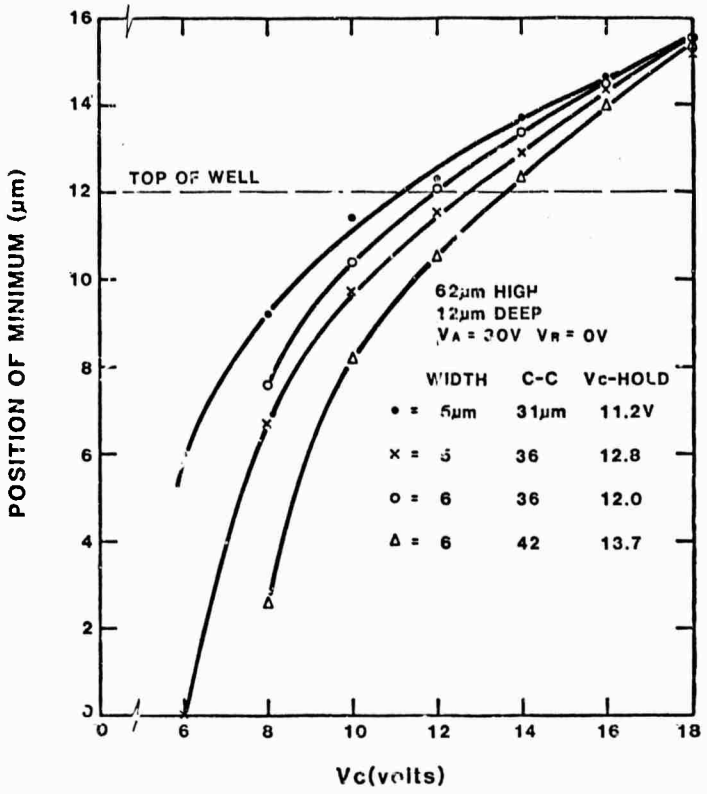


Figure 2

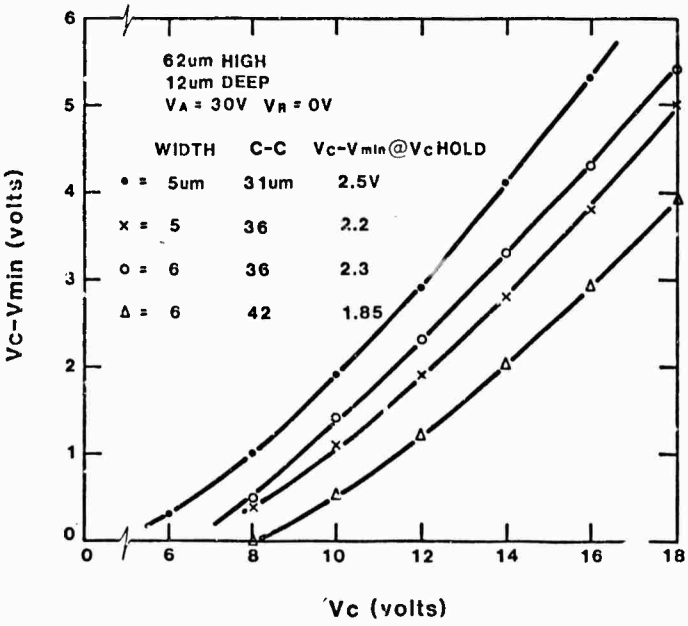


Figure 3

the bottom of the well and the potential minimum when that minimum is located at the top of the well.

Figures 4 and 5 illustrate the effects of spacing and wall width on the position and depth (in volts) of the potential minimum, respectively, at fixed electrode potentials. It can be seen in Figure 4 that the position of the minimum is about 0.3 μm higher for a 6 μm wall, everything else being equal. Similarly, from Figure 5 we see about 0.4 V increase in the depth of the potential minimum for a 6 μm wall.

Since a 6 μm wide wall results in greater holding power with lower voltage at the bottom of the well and is also easier to fabricate, we have chosen this dimension for the control grid electrode. Of the choices remaining, the 36 μm spacing is obviously superior to 42 μm. The opening in the well will be 30 μm x 102 μm, and the wall will be 6 μm wide. This gives 30 μm isolation lines for the grid electrodes. This geometry is underlined in Table 1. Finally, as explained in Par. 4.2, 62 μm was chosen as the overall thickness.

Calculations were then performed using the above dimensions and representative electrode potentials for all phases of device operation. Figures 6, 7, 8, 9 and 10 show the potential along the center line and equipotential contour maps for the "Erase", "Set", "Half-Select 1", "Half-Select 2", and "Write" phases of operation. Operation is visualized with the "a" figures and noting that the negative pigment particles will tend to move up along the potential gradient. Figure 11 is a 3-D view showing a case in which pigment is being held in the potential well. For clarity, the figure is inverted so that positive potential is down; thus the pigment position can be visualized as spheres rolling down the potential hill.

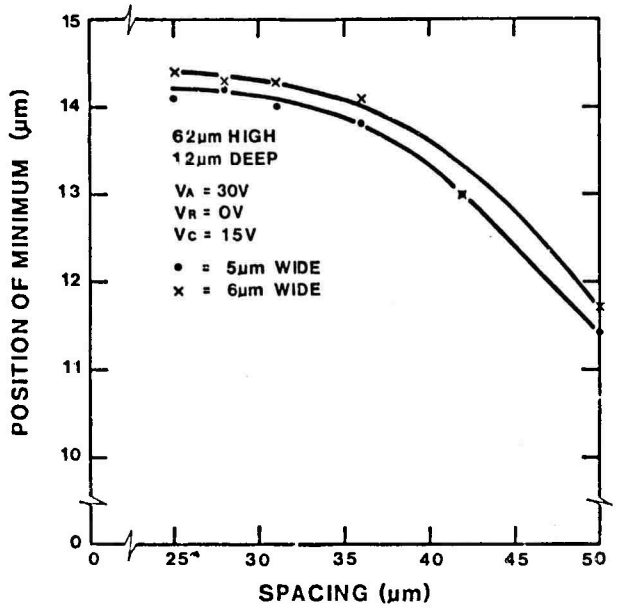
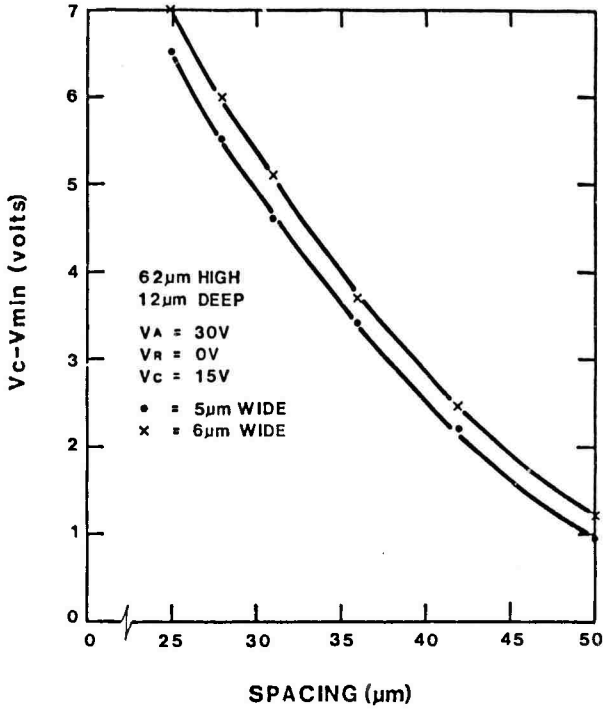


Figure 4



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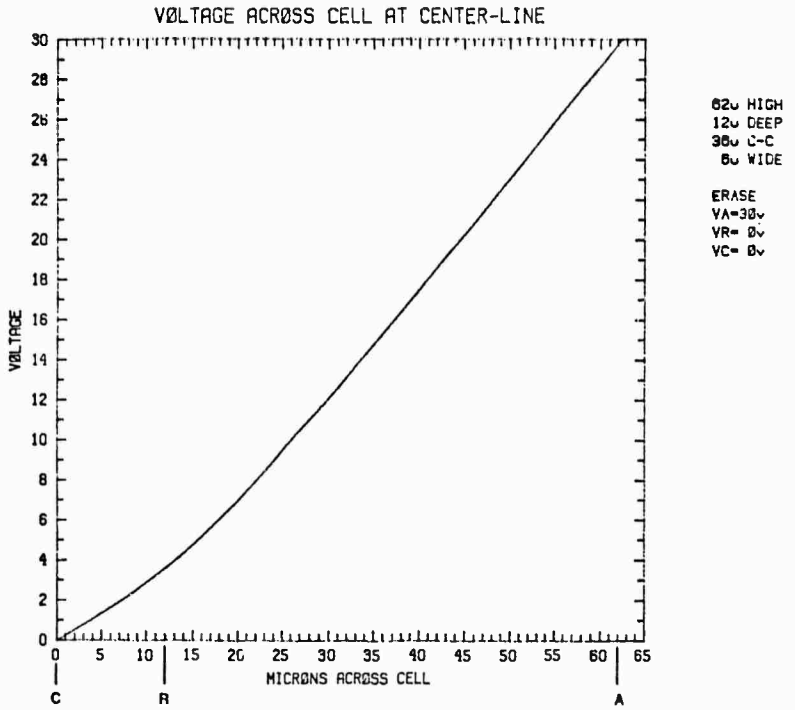
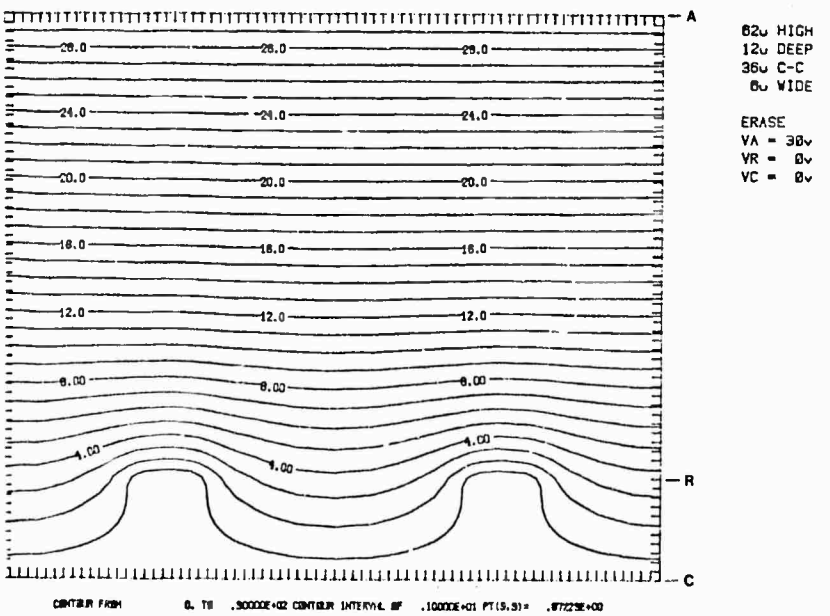
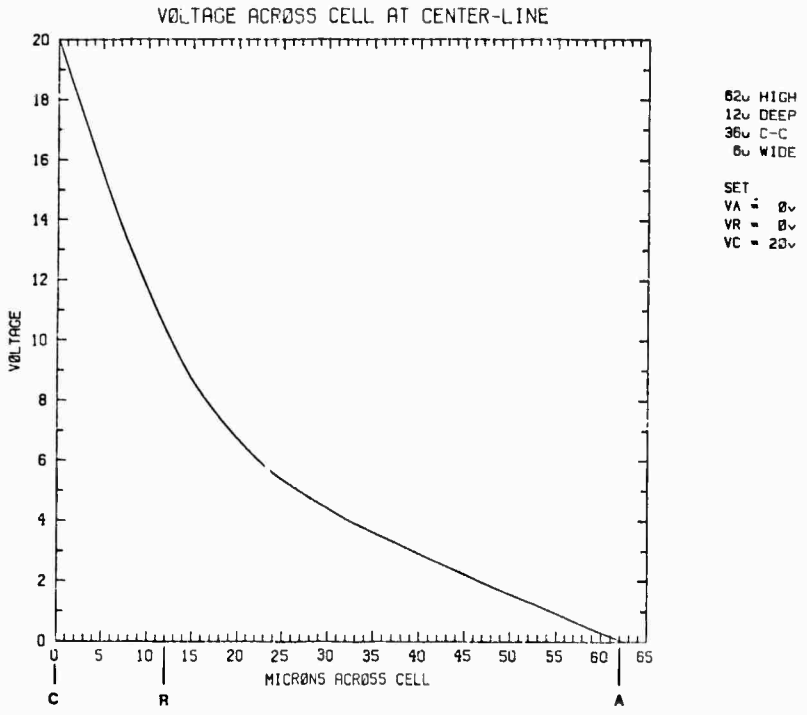

VØLTAGE ACRØSS CELL AT CENTER-LINE
VØLTAGE
MICRØNS ACRØSS CELL
C
R
A
62u HIGH
12u DEEP
36u C-C
6u WIDE
ERASE
VA=30v
VR= 0v
VC= 0v

(a)

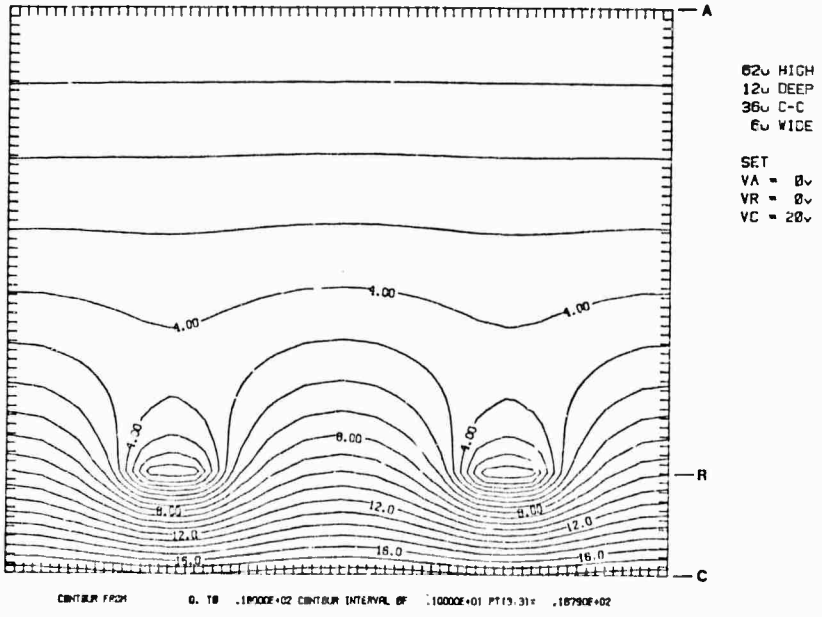

A
R
C
62u HIGH
12u DEEP
36u C-C
6u WIDE
ERASE
VA = 30v
VR = 0v
VC = 0v

(b)

Figure 6

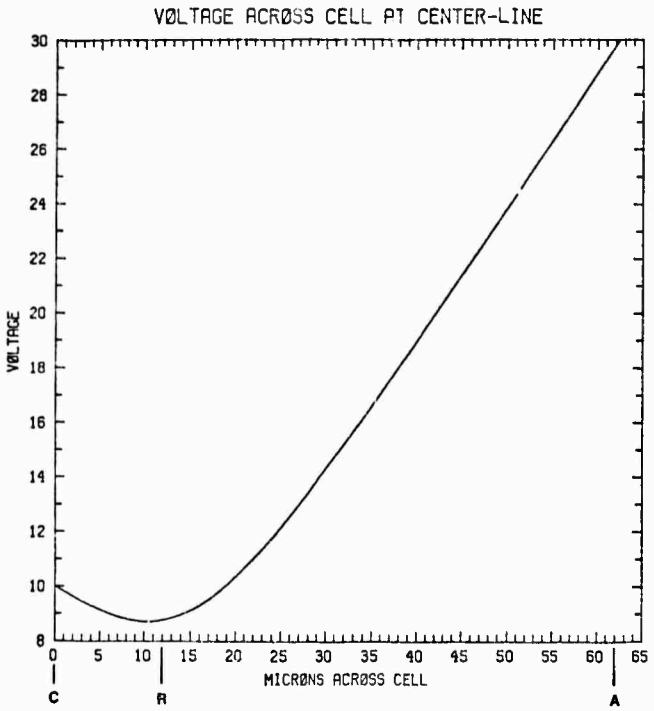

VØLTAGE ACRØSS CELL AT CENTER-LINE
VØLTAGE
MICRØNS ACRØSS CELL
C
R
A
62u HIGH
12u DEEP
36u C-C
6u WIDE
SET
VA = Øv
VR = Øv
VC = 20v

(a)

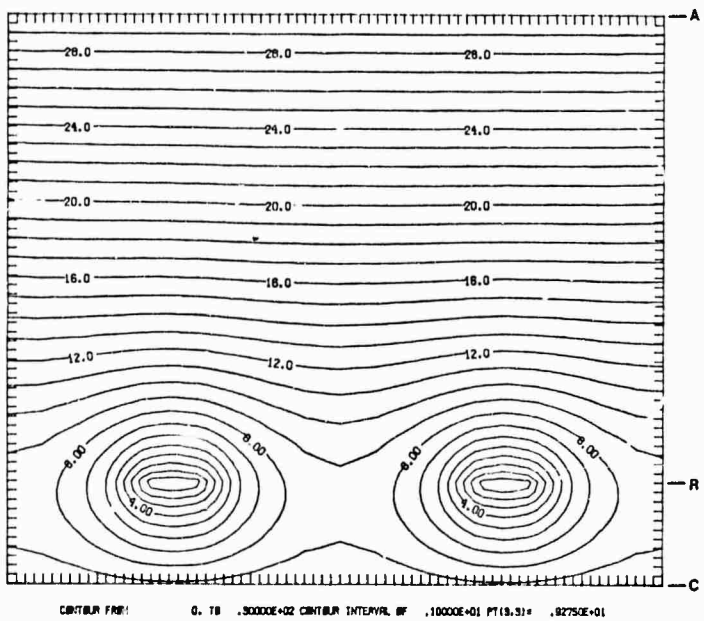

A
R
C
62u HIGH
12u DEEP
36u C-C
6u WIDE
SET
VA = Øv
VR = Øv
VC = 20v
4.00
8.00
12.0
16.0

(b)

Figure 7

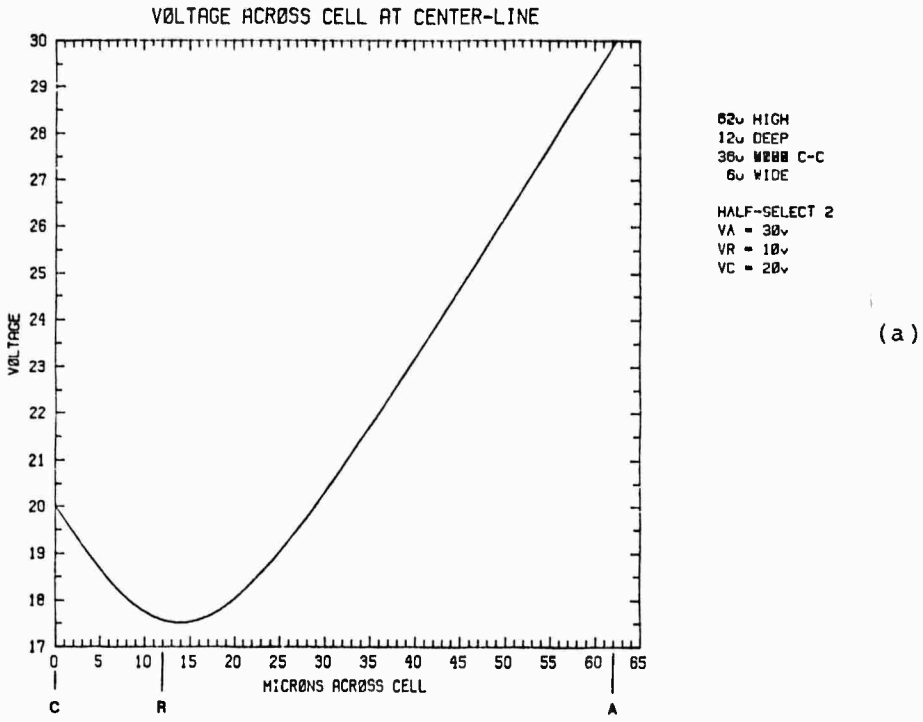

VØLTAGE ACRØSS CELL AT CENTER-LINE
VØLTAGE
MICRØNS ACRØSS CELL
C
R
A
62υ HIGH
12υ DEEP
36υ C-C
6υ WIDE
HALF-SELECT 1
VA = 30v
VR = 0v
VC = 10v

(a)


A
R
C
62υ HIGH
12υ DEEP
36υ C-C
6υ WIDE
HALF-SELECT 1
VA = 30v
VR = 0v
VC = 10v

(b)

Figure 8


VØLTAGE ACRØSS CELL AT CENTER-LINE
VØLTAGE
MICRØNS ACRØSS CELL
C
R
A
62υ HIGH
12υ DEEP
36υ C-C
6υ WIDE
HALF-SELECT 2
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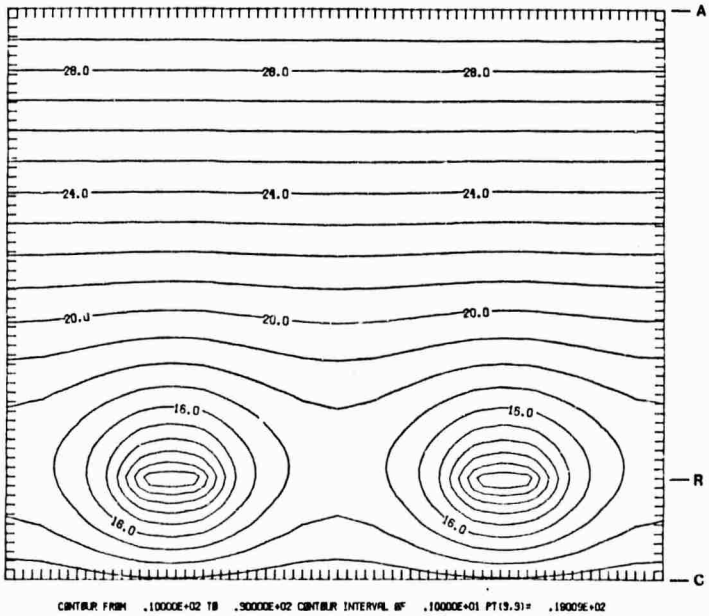
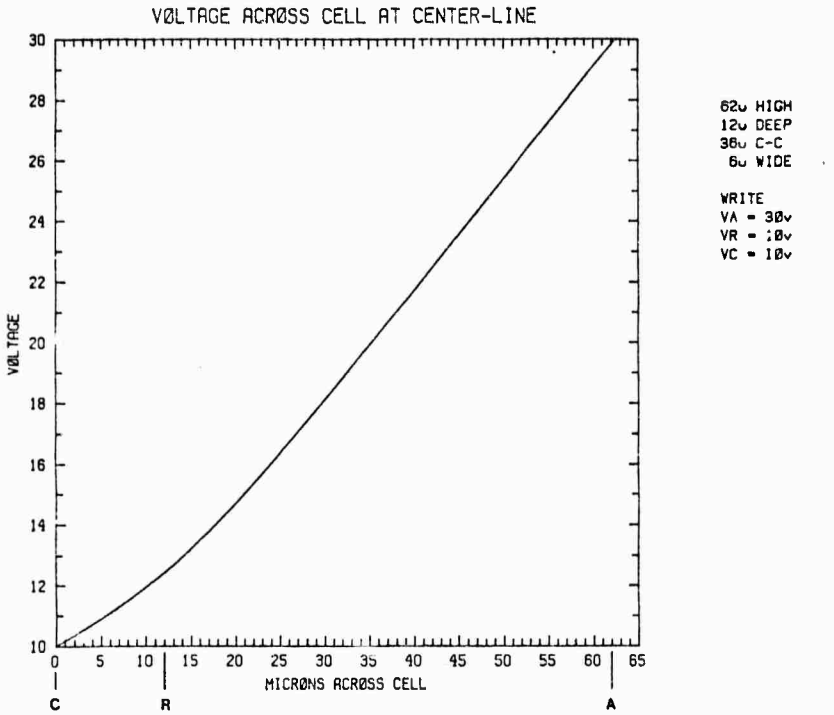
VR = 10v
VC = 20v

(a)

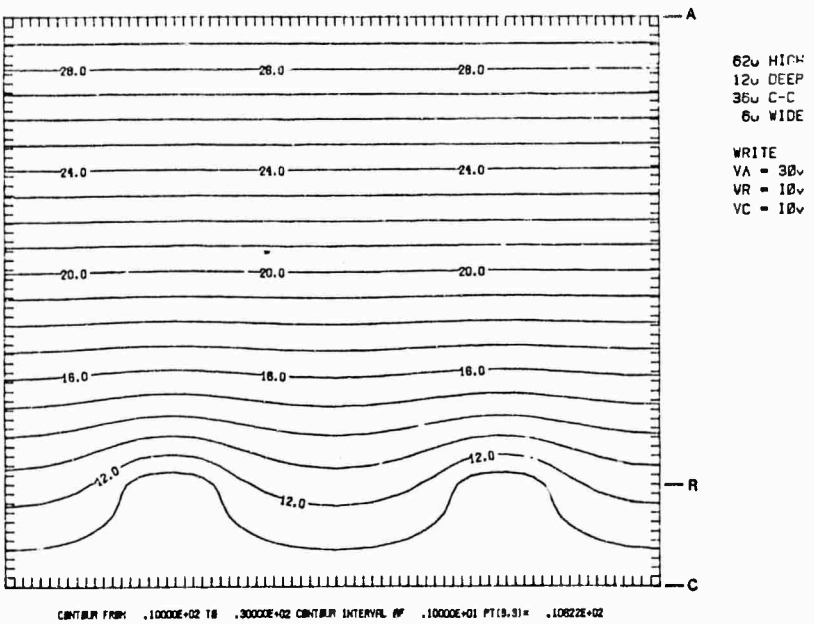

A
R
C
28.0
24.0
20.0
16.0
62υ HIGH
12υ DEEP
36υ C-C
6υ WIDE
HALF-SELECT 2
VA = 30v
VR = 10v
VC = 20v

(b)

Figure 9


VØLTAGE ACRØSS CELL AT CENTER-LINE
VØLTAGE
MICRØNS ACRØSS CELL
C
R
A
62u HIGH
12u DEEP
36u C-C
6u WIDE
WRITE
VA = 30v
VR = 10v
VC = 10v

(a)


28.0
24.0
20.0
16.0
12.0
A
R
C
62u HIGH
12u DEEP
36u C-C
6u WIDE
WRITE
VA = 30v
VR = 10v
VC = 10v

(b)

Figure 10

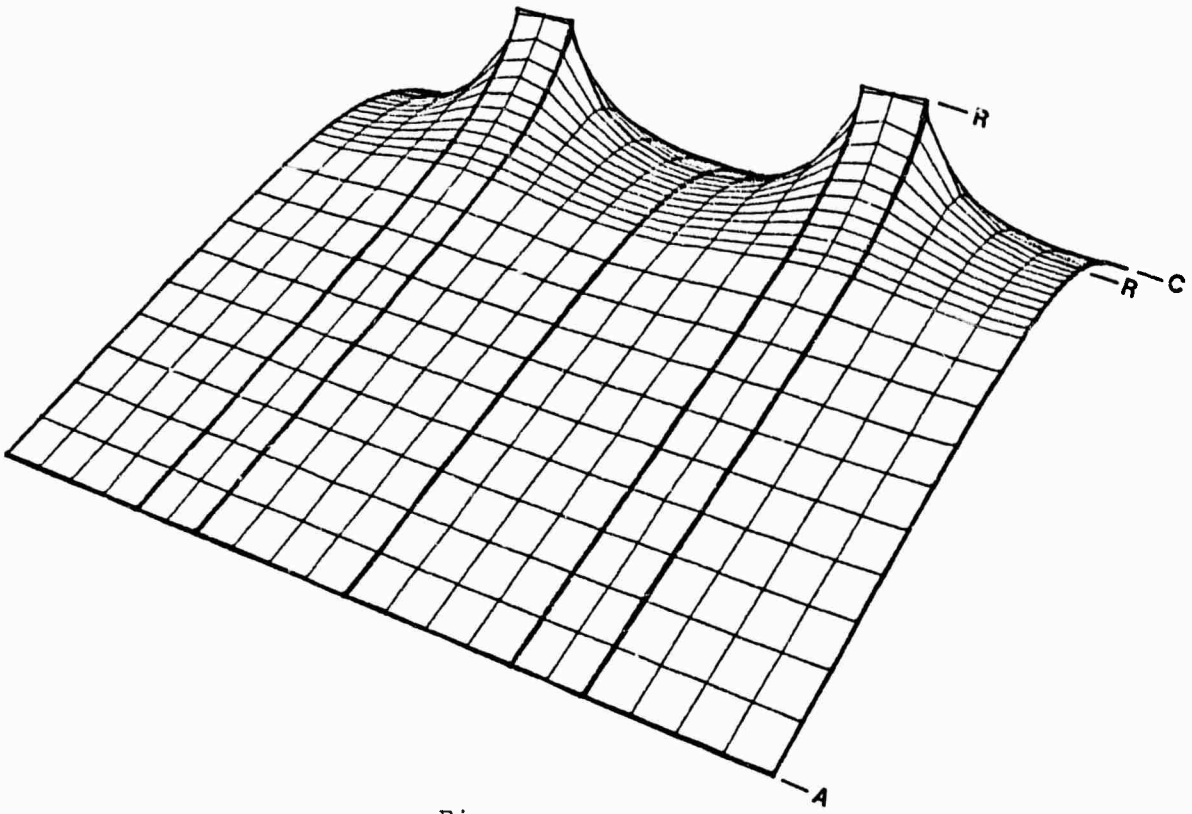


Figure 11

4.2 Designing the Display

As stated previously, there are basically two ways to position the perimeter seal. The 12 µm thick control grid could be fabricated totally within the perimeter seal area. This would necessitate making connection to the grid electrodes through the Mylar to In_2O_3 electrodes below, which would feed through the seal to the external connection pads. Since making such a large number of vias over 12 µm steps is deemed to be a low yield process, the other alternative has been chosen. In this case, the 12 µm Mylar would extend beyond the outside edge of the Mylar perimeter seal. This seal would be made on top of the 12 µm Mylar, and the grid electrodes would feed directly through the perimeter seal without the need for vias. These two methods result in separations of 50 µm and 62 µm, respectively, between opposite sides of the cell.

The active area of the display is rectangular. We have chosen to run the grid electrodes in the short direction (vertically) to minimize their resistance. We also have a choice in the direction of the long axis of the wells. The vertical direction is preferred since that results in more grid lines running parallel to the direction of current flow and in lower resistance. Also, since the display will generally be illuminated from above, there will be less diffraction from the grid lines because there will be fewer grid lines running perpendicular to the direction of illumination.

The design of the Phase I device is based upon: the proposed resolution of 2 lp/mm, the diagonal of the milled-area being less than 2.7 in., and rational digital driving requirements. This device will be capable of displaying 16 rows of 32 characters each. In order to accommodate these 512 characters in the available space and achieve good readability, a 5 x 7 dot matrix font was chosen with two pixels between characters, both horizontally and vertically. Thus, each character position occupies 7 x 9 pixels. There will be over 32,000 individually

addressable elements in this display with less than 400 connections to the drive electronics. The active area will be 2.23 in. x 1.44 in., with a diagonal of 2.65 in. Figure 12 shows an actual-size mockup of the display. The row and column contacts will be brought out on all four sides. With space left for the seal and contacts, the overall size of the device will be about 3 in. x 2.2 in. Figure 13 is a mockup of the proposed 600 x 350 pixel display.

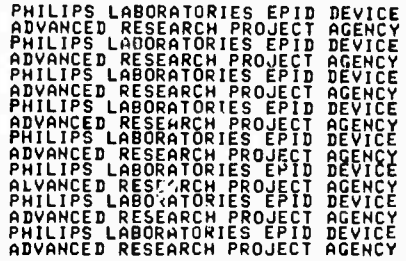


Figure 12

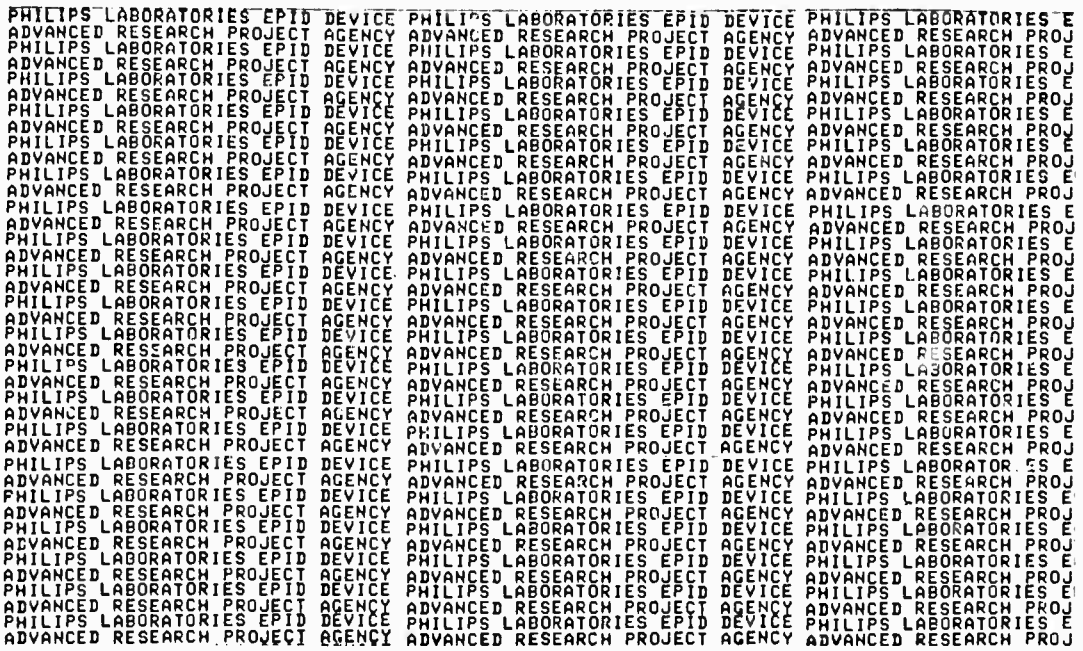


Figure 13

5. PLANS FOR NEXT QUARTER

a. Investigate SiO_x protective layers.

b. Finish mask drawings and order masks.

c. Set up In_2O_3/SnO_2 sputtering system.

d. Fabricate a working large-area device and test suspensions.

e. Continue materials compatibility tests.

f. Start design of driver.

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